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14. ABSTRACT
Layered magnetostrictive-ferroelectric structures are multifunctional due to their response to mechanical and electromagnetic forces. Investigations on microwave magneto-electric (ME)interactions were performed on ferrite-ferroelectrics layered structures. Systems studied include yttrium iron garnet (YIG)-lead zirconate titanate (PZT) or YIG-barium strontium titanate (BST). Our efforts have resulted in the following breakthroughs in experimental and theoretical understanding: (i) The observation of strong microwave ME interactions in YIG-PZT; (ii) Theory and experiments on the creation and propagation characteristics of hybrid spin-electromagnetic waves in YIG-BST; and (iii) Fabrication of electric field

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Report Title

Microwave and millimeter wave magnetoelectric interactions in engineered multiferroics and dual electric and magnetic field tunable devices

ABSTRACT

Layered magnetostrictive-ferroelectric structures are multifunctional due to their response to mechanical and electromagnetic forces. Investigations on microwave magneto-electric (ME)interactions were performed on ferrite-ferroelectrics layered structures. Systems studied include yttrium iron garnet (YIG)-lead zirconate titanate (PZT) or YIG-barium strontium titanate (BST). Our efforts have resulted in the following breakthroughs in experimental and theoretical understanding: (i) The observation of strong microwave ME interactions in YIG-PZT; (ii) Theory and experiments on the creation and propagation characteristics of hybrid spin-electromagnetic waves in YIG-BST; and (iii) Fabrication of electric field tunable YIG-PZT and YIG-BST resonators and phase shifters operating at 3-12 GHz. These results have been published in 35 journal articles.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. "Microwave magnetoelectric effects in single crystal bilayers of yttrium iron garnet and lead magnesium niobate-lead titanate," S. Shastry, G. Srinivasan, M. I. Bichurin, V. M. Petrov, and A. S. Tatarenko, Phys. Rev. B. 70, 064416 (2004).
2. "Resonant Magnetoelectric Coupling in Trilayers of Ferromagnetic Alloys and Piezoelectric Lead Zirconate Titanate: The Influence of Bias Magnetic Field," G. Srinivasan, C. P. DeVreugd, V. M. Laletin, N. Paddubnaya, and M. I. Bichurin, Phys. Rev. B. 71, 184423 (2005).
3. "Magnetoelectric Interactions in Bilayers of Yttrium Iron Garnet and Lead Magnesium Niobate-Lead Titanate : Evidence for Strong Coupling in Single Crystals and Epitaxial Films," G. Srinivasan, C. P. De Vreugd, M. I. Bichurin, and V. M. Petrov, Appl. Phys. Lett. 86, 222506 (2005).
4. "Ferromagnetic-ferroelectric layered structures: Magnetoelectric interactions and devices," G. Srinivasan, M. I. Bichurin, and J. V. Mantese, Integ. Ferroelec. 71, 45 (2005).
5. "Electrically tunable microwave filters based on ferromagnetic resonance in single crystal ferrite-ferroelectric bilayers," A. S. Tatarenko, M. I. Bichurin and G. Srinivasan, Elec. Lett. 41, 596 (2005).
6. "Electrically tunable ferrite-ferroelectric microwave delay lines," Y. K. Fetisov and G. Srinivasan, Appl. Phys. Lett. 87, 103502 (2005).
7. "Theory of magnetoelectric effects at magneto-acoustic resonance in single crystal ferromagnetic-ferroelectric heterostructures," M. I. Bichurin, V. M. Petrov, O. V. Ryabkov, S. V. Verkin, and G. Srinivasan, Phys. Rev. B 72, 060408 (R) 2005.
8. "A ferrite/piezoelectric microwave phase shifter: Studies on electric field tunability," Y. K. Fetisov and G. Srinivasan, Elec. Lett. 41, 1066 (2005).
9. "The floating zone crystal growth of ni, Co, Ni-Co, Ni-Zn, and Co-Zn ferrospinels under high oxygen pressure," A. M. Balbashov, L. N. Rybina, Y. K. Fetisov, V. F. Meshcheryakov, and G. Srinivasan, J. Crys. Growth 175, e733 (2005).
10. "Electric field induced shift of the magnetic resonance line in ferrite-piezoelectric composites, " O. V. Antonenkov, M. I. Bichurin, D. A. Filippov, V. M. Petrov, and G. Srinivasan, Tech. Phys. Lett. 31, 673 (2005).
11. C.Bayer, J.Jorzick, S.O.Demokritov, B.Hillebrands, R.Kouba, R.Bozinoski, A.N.Slavin, K.Guslienko, D.Berkov, N.Gorn, M.P.Kostylev, "Spin-wave excitations in finite rectangular elements of Ni80Fe20" , Phys.Rev.B 72 , 064427 (2005).
12. K.Yu. Guslienko, and A.N. Slavin, "Boundary conditions for magnetization in magnetic nanoelements", Phys. Rev. B 72, 014463 (2005).
13. A. N. Slavin and V. S. Tiberkevich, " Current-induced bistability and dynamic range of microwave generation in magnetic nano-structures", Phys. Rev. B 72, 094428 (2005).
14. A.N. Slavin and V.S. Tiberkevich, "Nonlinear self-phase-locking in an array of current-driven magnetic nano-contacts", Phys. Rev. B 72, 092407 (2005).
15. Slavin A.N., Kabos P., "Approximate theory of microwave generation in a current-driven magnetic nanocontact magnetized in an arbitrary direction", IEEE Trans. Magn. 41 , 1264-1273 (2005).
16. "Ferrite-ferroelectric layered structures for electrically and magnetically tunable microwave resonators," A. A. Semenov, S. F. Karmanenkov, V. E. Demidov, B. A. Kalinikos, G. Srinivasan, A. N. Slavin, and J. V. Mantese, Appl. Phys. Lett. 88, 033503 (2006).
17. "Magnetoelectric coupling in bilayers of Pb(Zr,Ti)O3 epoxy and hot pressed manganite perovskite," N. Zhang, X. Yin, M. Wang, T. Schneider, and G. Srinivasan, Chin. Appl. Phys. Lett. 23, 463 (2006).
18. "Electric field tuning characteristics of a ferrite-piezoelectric microwave resonator," Y. K. Fetisov and G. Srinivasan, Appl. Phys. Lett. 88, 143503 (2006).
19. "A magnetoelectric microwave phase shifter," A. S. Tatarenko, G. Srinivasan and M. I. Bichurin, Appl. Phys. Lett. 88, 183507 (2006).
20. "A Magnetoelectric Microwave Band-Pass Filter," A.S. Tatarenko, V. Gheevarughese, G. Srinivasan, Elec. Lett. 42, 540 (2006).
21. "Dual-Tunable Hybrid Wave Ferrite-Ferroelectric Microwave Resonator," A.A. Semenov, S.F. Karmanenko, B.A. Kalinikos, G. Srinivasan, A.N. Slavin, J.V. Mantese, Elec. Lett. 42, 641 (2006)
22. "Ferrite-piezoelectric multilayers for magnetic field sensors," Y. Fetisov, A. Bush, K. Kamentsev, A. Ostashchenko, and G. Srinivasan, IEEE Sensors 6, 935 (2006).
23. "Microwave magnetoelectric effects and signal processing devices," G. Srinivasan and Y. K. Fetisov, Integrated Ferroelectrics 83, 89 (2006).
24. "Millimeter-wave magnetoelectric effects in bilayers of barium hexaferrite and lead zirconate titanate," G. Srinivasan, I. V. Zavislyak, and A. S. Tatarenko, Appl. Phys. Lett. 89, 152508 (2006).
25. "Electric field tunable ferrite-ferroelectric hybrid wave microwave resonators: Experiment and Theory," A. B. Ustinov, V. S. Tiberkevich, G. Srinivasan, A. N. Slavin, A. A. Semenov, S. F. kamanenko, B. A. Kalinikos, J. V. Mantese, and R. Ramer, J. Appl. Phys. 100, 093905 (2006).
26. "Magnetoacoustic resonance in tangentially magnetized ferrite-piezoelectric bilayers," O.V. Ryabkov, V. M. Petrov, M. I. Bichurin, and G. Srinivasan, Tech. Phys. Lett. 32, 1021 (2006).
27. "Microwave magnetoelectric interactions in multiferroics," G. Srinivasan, A. S. Tatarenko, Y. K. Fetisov, V. Gheevarughese, and M. I. Bichurin, MRS proceedings, 2006.
28. "Ferrite-piezoelectric layered structures: Microwave magnetoelectric effects and electric field tunable devices," G. Srinivasan and Y. K. Fetisov, Ferroelectrics 342, 65 (2006).

29. S.O. Demokritov, V.E. Demidov, O. Dzyapko, G.A. Melkov, A.A. Serga, B. Hillebrands, and A.N. Slavin, "Bose-Einstein condensation of quasi-equilibrium magnons at room temperature under pumping", Nature 443, 430-433 (2006).
30. V.E.Demidov, U.-F. Hansen, O. Dzyapko, N. Koulev, S.O. Demokritov and A.N. Slavin, "Formation of longitudinal patterns and dimensionality crossover of nonlinear spin waves in ferromagnetic stripes", Phys.Rev.B 74, 092407 (2006).
31. "Ferrite-ferroelectric hybrid wave phase shifters," A. Ustinov, G. Srinivasan, and B. A. Kalinikos, Appl. Phys. Lett. 90, 031913 (2007).
32. "Microwave magnetoelectric interactions in multiferroics," G. Srinivasan, A. S. Tatarenko, Y. K. Fetisov, V. Gheevarughese, and M. I. Bichurin, Mater. Res. Soc. Symp. Proc. 966, T-14-01, (2007).
33. "Structure, magnetism and tunable microwave properties of PLD-grown barium ferrite/barium strontium titanate bilayer films" R. Heindl, H. Srikanth, S. Watanachchi, P. Mukherjee, T. Weller, A. S. Tatarenko, and G. Srinivasan, J. Appl. Phys. 101, 09M503 (2007).
34. "A magnetoelectric microwave attenuator," A.S. Tatarenko, G. Srinivasan, and D. A. Filippov, Elec. Lett. 43, 674 (2007).
35. "Magnetoelectric interactions in a ferromagnetic-piezoelectric layered structures: Phenomena and devices," M. I. Bichurin, D. Viehland and G. Srinivasan, in press, J. Elec. Ceramics (2007).
36. "Theory of electric field induced magnetic excitations in ferrite-piezoelectric nanobilayers," V. Petrov and G. Srinivasan, O. V. Ryabkov, S. V. Averkin, and M. I. Bichurin," in press, Solid State Commun.
37. A. B. Ustinov, B. A. Kalinikos, V. S. Tiberkevich, A. N. Slavin, and G. Srinivasan, "Q-factor of Dual-Tunable Microwave Resonators Based on Yttrium Iron Garnet and Barium Strontium Titanate Layered Structures", submitted to Journal of Applied Physics (2007).

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(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

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(c) Presentations

1. “Correlation of magnetoelectric and delta ferromagnetic-piezoelectric layered composites,” V. M. Laletin, N. Paddubnaya, G. Srinivasan, C. P. De Vreugd, ¿. I. Bichurin, V. M. Petrov and D. A. Filippov, presented at the American Physical Society March meeting, Los Angeles, 2005.

2. “Magnetoelectric susceptibility dispersion of ferrite - piezoelectric composites,” V.M. Petrov, M. I. Bichurin ,O.V.Ryabkov, and G. Srinivasan, presented at APS March meeting, 2005.
3. “Magnetoelectric Composite Based Microwave Attenuator,”A. S. Tatarenko, M. I. Bichurin, A.A. Charlamov, D.A. Filippov, G. Srinivasan, presented at APS March meeting, 2005.
4. “Magnetoelectric effect in porous bulk ferromagnetic/piezoelectric composites,” M. I. Bichurin, V. M Petrov, D. S. Tuskov, and G. Srinivasan, presented at APS March meeting, 2005.
5. “Theory of electromechanical resonance in magnetostrictive - piezoelectric multilayer composites,” D. A. Filippov, V.M. Petrov, M. I. Bichurin, C. W. Nan, and G. Srinivasan, presented at APS 2005.
6. “Field induced fluctuations in percolation in granular-heterogeneous La-Ag-Mn-O/ MnO,” N. Zhang and G. Srinivasan, presented at APS 2005.
7. “An Electrically Tunable Barium Strontium Titanate Phase Shifter,” S. F. Karmanenko, A. A. Semenov, B. A. Kalinikos, A. N. Slavin, G. Srinivasan, and J. V. Mantese, presented at APS 2005.
8. “A 30-GHz Hexagonal Ferrite Phase Shifter,” S. F. Karmanenko, A. S. Semenov, B. A. Kalinikos, A. Slavin, G. Srinivasan, J. V. Mantese, presented at APS 2005.
9. “Low Frequency Magnetoelectric Coupling in Bilayers of Lead Zirconate Titanate and Sol-gel Derived Lanthanum Strontium Manganite,” Wei Yang, Ning Zhang and G. Srinivasan, presented at APS 2005.
10. “Magnetoelectric interactions in single crystal ferrite-piezoelectric bilayers,” G.Srinivasan, C. P. DeVreugd, C. S. Flattery, V. M. Petrov, M. I. Bichurin and A. A. Ivanov, J. Zhai, S. Dong and D. Viehland, presented at APS 2005.
11. “Electric dipole transitions at magnetoacoustic resonance,” M.I. Bichurin, V. M. Petrov, O.V. Ryabkov, A.V. Filippov, A.A. Ivanov, and G. Srinivasan, presented at the 2006 APS March meeting –Baltimore.
12. “Enhancement in magnetoelectric effects at thickness modes of layered ferromagnets and ferroelectrics,” D.A. Filippov, M.I. Bichurin, V. M. Petrov, V.M. Laletin, G. Srinivasan, and C.-W. Nan, presented at the 2006 APS March meeting –Baltimore.
13. A magnetic field tunable left handed lens,” G. Srinivasan, R.V. Petrov, M.I. Bichurin, A.S. Petrov, D. Viehland. presented at the 2006 APS March meeting –Baltimore.
14. A negative-index metamaterial unit cell,” R.V. Petrov, M. I. Bichurin, G. Srinivasan, and D. Viehland, presented at the 2006 APS March meeting –Baltimore.
15. “Static field anisotropies in a composition-graded ferroics,” J.V. Mantese, A.L. Micheli, N.W. Schubring, R.V. Hayes, and G. Srinivasan, presented at the 2006 APS March meeting –Baltimore.
16. “A magnetoelectric microwave filter,” A.S. Tatarenko, G. Srinivasan, and M.I. Bichurin, presented at the 2006 APS March meeting –Baltimore.
17. “A YIG-PZT microwave phase shifter,” G. Srinivasan, A. S. Tatarenko, and M.I. Bichurin, presented at the 2006 APS March meeting –Baltimore.
18. “Ferromagnetic-ferroelectric layered structures for microwave signal processing,” G. Srinivasan, presented at the International Symposium on Integrated Ferroelectrics, April 2006. Hawaii.
19. “Electric dipole transitions at magnetoacoustic resonance,” M. I. Bichurin, V. M. Petrov, O. V. Ryabkov, Filippov A.V. and Ivanov A.A. (Novgorod State University, Russia), and G. Srinivasan (Oakland University, Rochester, MI) - presented at the APS March meeting.2007
20. “Enhancement in magnetoelectric effects at thickness modes of ferrite-ferroelectric bilayers,” D. A. Filippov, M. I. Bichurin, V. M. Petrov (Novgorod State University, Russia), V. M. Laletin (Institute of Technical Acoustics, Vitebsk, Belarus), G. Srinivasan (Oakland University, Rochester, MI) and C.W. Nan (Tsinghua University, China) - presented at APS March meeting. 2007
21. “A Magnetic Field Tunable Lens of Left Handed Materials,” G. Srinivasan (Oakland University, Rochester, MI 48309), R.V.Petrov , M. I. Bichurin , A.S.Petrov ,(Novgorod State University, B.S.Peterburgskaya St. 41, 173003 Veliky Novgorod, Russia), D. Viehland (Virginia Tech, Blacksburg,VA 24061) - presented at the APS March meeting – 2007.
22. “A Negative-Index Metamaterial Unit Cell,” R. V. Petrov and M. I. Bichurin (Novgorod State University, B.S.Peterburgskaya St. 41, 173003 Veliky Novgorod, Russia), D. Viehland, (Virginia Tech, Blacksburg,VA 24061), G. Srinivasan (Oakland University, Rochester, MI 48309). - presented at the APS March meeting – 2007.
23. “A yttrium iron garnet-lead zirconate titanate microwave phase shifter,” G. Srinivasan and A.S. Tatarenko (Physics Department, Oakland University), M.I. Bichurin
(Institute of Electronic and Information System, Novgorod State University, Russia).- presented at the APS March meeting – 2007.

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(d) Manuscripts

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Alexey Ustinov	1.00
Alexander Semenov	1.00
Yuri Fetisov	1.00
Roman Petrov	0.33
Alexander Tatarenko	0.25
Igor Zavislyak	0.50
V.S. Tiberkevich	0.20
FTE Equivalent:	**4.28**
Total Number:	**7**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Gopalan Srinivasan	0.08	No
Andrei Slavin	0.08	No
FTE Equivalent:	**0.16**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
David Elliott	0.00
Saurub Pandey	0.00
FTE Equivalent:	**0.00**
Total Number:	**2**

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	2.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	2.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	2.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):	2.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

NAME
Russell Hayes
Christopher Flattery
Vincy Gheevarughese
Santhi Sukumar
Christopher DeVreugd

Total Number: **5**

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED	
John Colling	1.00	No
FTE Equivalent:	**1.00**	
Total Number:	**1**	

Sub Contractors (DD882)

Inventions (DD882)

FINAL REPORT

Microwave and millimeter wave magnetoelectric interactions in engineered multiferroics and dual electric and magnetic field tunable devices

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Rochester, MI 48309

Abstract

Layered magnetostrictive-ferroelectric structures are multifunctional due to their response to mechanical and electromagnetic forces. Investigations on microwave magneto-electric (ME)interactions were performed on ferrite-ferroelectrics layered structures. Systems studied include yttrium iron garnet (YIG)-lead zirconate titanate (PZT) or YIG-barium strontium titanate (BST). Our efforts have resulted in the following breakthroughs in experimental and theoretical understanding: (i) The observation of strong microwave ME interactions in YIG-PZT; (ii) Theory and experiments on the creation and propagation characteristics of hybrid spin-electromagnetic waves in YIG-BST; and (iii) Fabrication of electric field tunable YIG-PZT and YIG-BST resonators and phase shifters operating at 3-12 GHz. These results have been published in 35 journal articles.

Research Accomplished and Major findings

Layered multiferroics are of current interests for studies on the physics of ME interactions and for useful devices. The ARO support facilitated fundamental work on microwave ME interactions and the design and characterization of dual electric and magnetic field tunable devices [1-32]. Studies focused on the physics and novel device concepts related to two important effects: (i) ME coupling between *tightly bound* layers influencing the frequency of ferromagnetic resonance and (ii) ME coupling between *unbound* layers leading to the creation of hybrid spin-electromagnetic waves. Key accomplishements include the following.

- Resonance magnetoelectric effects in ferrite-piezoelectric bilayers, at ferromagnetic resonance for the ferrite. The ME coupling was measured from data on FMR shifts in an applied electric field E. Low-loss yttrium iron garnet (YIG) was used for the ferromagnetic phase. Single crystal lead magnesium niobate-lead titanate (PMN-PT) and PZT were used for the ferroelectric phase.
- Theory and measurements on hybrid spin-electromagnetic waves that originate from ME interactions in layered YIG-BST structures, and theory of microelectronic hybrid-wave resonators.
- Design, fabrication, and analysis of composite based devices, including resonators and phase shifters. The unique for such devices is the tunability with E.

There have been many breakthroughs in both experiments and theoretical understanding of the phenomenon. We provide here a brief outline of key accomplishments.

1. Microwave ME effects in ferrite-piezoelectrics: Theory and Experiment

In the microwave region of the electromagnetic spectrum, the ME effect can be observed in the form of a shift in FMR profile in E (Fig.1). Mechanical stress in the ferroelectric arising from E is coupled to the ferrite, leading to a shift δH_z in the FMR as in Fig.2. Theoretical FMR profiles based on our model are

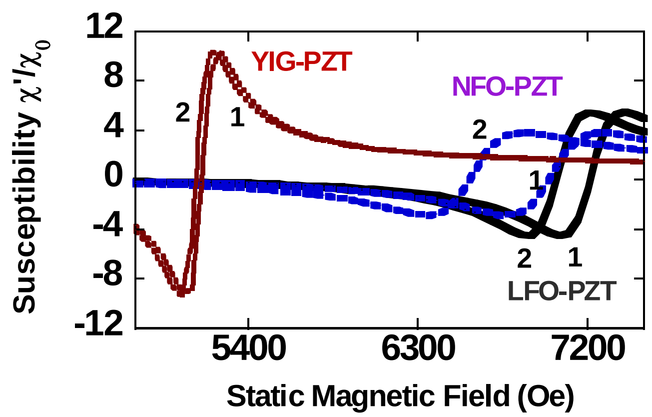

Fig.1: Theoretical FMR profiles in ferrite-PZT bilayers at 9.3 GHz for E=0 (labeled –1) and E = 300 kV/cm(-2). E and H are perpendicular to the bilayer. [Ref.22]

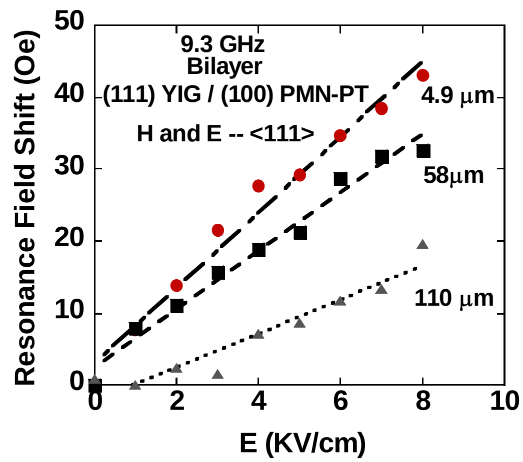

Fig.2: Data on FMR field shift vs. E for a YIG/PMN-PT bilayer. [Ref.23]

shown in Fig.1 for bilayers with YIG, nickel ferrite (NFO), or lithium ferrite (LFO) and PZT. For E = 300 kV/cm, a shift in the resonance field δH_E that varies from a minimum of 22 Oe for YIG/PZT to a maximum of 330 Oe for NFO-PZT is predicted [21,22]. The strength of ME interactions $A = \delta H_E/E$ is determined by piezoelectric coupling and magnetostriction. Figure 2 shows our data on δH_z vs E at 9.3 GHz for a bilayer of YIG and PMN-PT and the ME effect is an order of magnitude stronger than predictions in Fig.1 for YIG/PZT. *The data also provide evidence for electric field tunability of YIG microwave devices.*

2. Hybrid spin-electromagnetic waves in ferrite-dielectrics: Theory and Experiment

The ME effect discussed above takes place in bilayered ferrite-ferroelectric structures when the layers are *tightly bound* i.e. when the mechanical stress created in one layer is transferred to the neighboring layer. There are, however, other ME phenomena that do not require bonding between the layers and take place simply due to the proximity of two material having different dielectric and magnetic properties [31]. An example of such a phenomenon is the formation of hybrid spin-electromagnetic waves in the layered structures. The nature of the hybrid waves were studied in a YIG-BST structure shown in Fig.3. The dimensions for the YIG and BST were chosen to be equal in order to maximize the electromagnetic coupling between FMR in YIG and dielectric resonance in BST. Both H- and E-dependence of the hybrid excitations, due to variations in μ and ε, were measured (Fig.4) and compared with theory [31].

The key result is the tunability of the mode by 100 MHz for nominal E and would facilitate the fabrication of E-tunable YIG-BST resonators for microwave circuits.

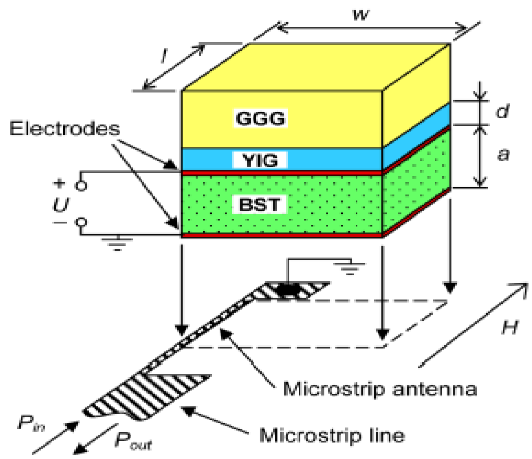

Fig.3: Diagram showing the schematics of a YIG-BST layered system for hybrid

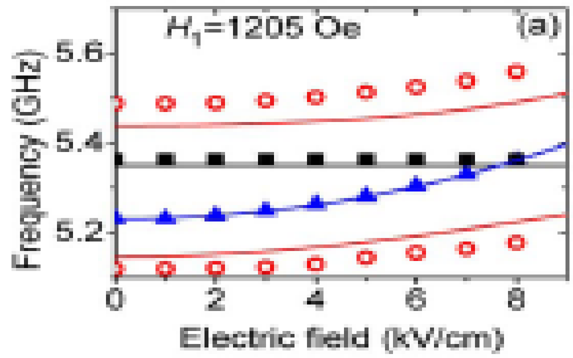

Fig.4: Dependences of resonant frequencies on E. Open circles are resonance frequencies of the YIG-BST resonator, and the solid squares and triangles are resonant frequencies of YIG and BST resonators

3. Electric field tunable microwave devices: YIG-PZT and YIG-BST resonators

The above studies on microwave ME effects in YIG-PZT, YIG-PMNPT, and YIG-BST led to the design, fabrication and characterization of a new family of novel signal processing devices that are tunable by both magnetic and electric fields. The device studied under ARO support included YIG-PZT and YIG-BST resonators [28-31]. *We also have an ONR grant for "Electric field Tunable Ferrite Devices" and supported our efforts on filters, phase shifters and delay lines [26,27,34-37].*

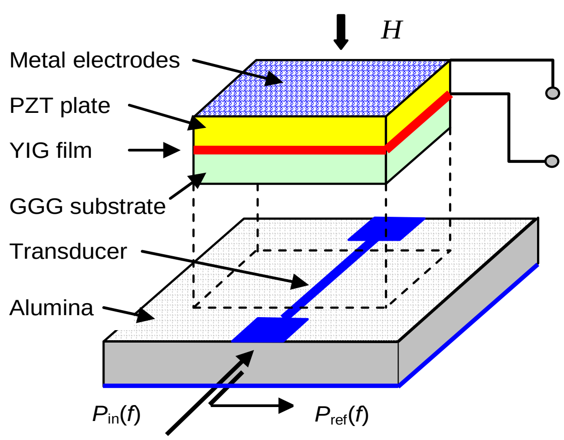

Fig.5: YIG-PZT resonator. [Ref.28]

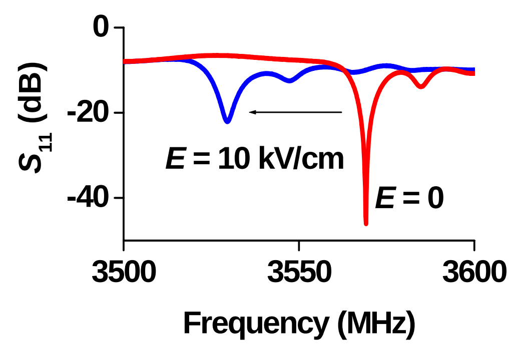

Fig.6: Electric field tunable 13 μm YIG-PMN-PT resonator with perpendicular magnetization (H = 3010 Oe). [Ref.28]

We have extended the studies described in d.1 and d.2 to include electric field effects in YIG resonators [28-31]. Bilayers were made by bonding epitaxial YIG films and single crystal PMN-PT or PZT. Stripline resonators (Fig.5) were subjected to perpendicular or parallel *H*. Figure 6 shows the resonator response for *an electric field across PMN-PT*: a shift δf_E, positive or negative depending on the H direction, is seen. The tuning obtained here, δH_E = 50 MHz for *E*=10 kV/cm, is 10 times the width of FMR in YIG and is suitable for device applications. The resonator Q ranged from 1000-2000. With proper choice of the ferrite and piezoelectric phases and *E*-value, a tuning range of 0.5-1 GHz is quite possible.

Similarly, YIG-BST hybrid wave resonators showed Q = 1000 and electric field tunability on the order of 0.1% of the operating frequency [31].

It is clear from the discussions here that ME interactions are very strong in the microwave region in bound and unbound ferrite-ferroelectric bilayers and that a family of dual electric and magnetic field tunable ferrite-ferroelectric resonators, filters, and phase shifters can be realized. The electric field tunability, in particular, is 0.1% or more of the operating frequency of filters and resonators. A substantial differential-phase shift can also be achieved for nominal electric fields. This proposal addresses similar investigations on mm-wave ME interactions in hexagonal ferrite-ferroelectric-dielectric structures.

4. <u>YIG/PMN-PT resonators:</u> Electrically and magnetically tunable microwave resonators based on ferrite-piezoelectric layered structure have been investigated. The structure consisted of bonded layers of single-crystal yttrium iron garnet (YIG) film and single-crystal lead magnesium niobate-lead titanate (PMN-PT) slab. The frequency of the resonator was tuned in over a wide frequency range, from 3 to 10 GHz, by varying the bias magnetic field (magnetic tuning) and over a narrow range, up to 45 MHz, by the application of an electric field (electric tuning) to the PMN-PT layer. Performance characteristics of the resonator are discussed. The data are in good agreement with theory. (Figs.7 and 8). The resonator could be useful as a band-pass or band-stop filter.

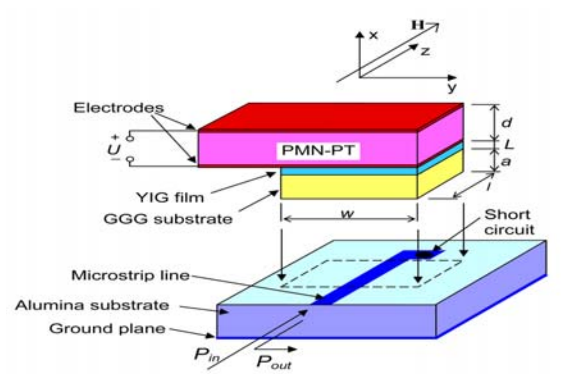

Fig.7: Block-diagram of the YIG/PMN-PT resonator.

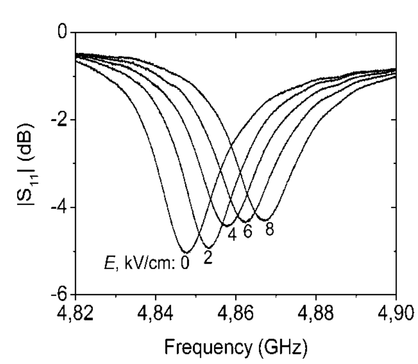

Fig.8: Shift of resonance frequency of the YIG/PMN-PT resonator with applied electric field E measured for H=1012 Oe, f=4.8478 GHz.

5. <u>YIG-BST Phase shifter</u>: A dual, electric and magnetic field tunable microwave phase shifter based on the propagation of hybrid spin-electromagnetic waves in YIG-BST bilayer has been designed and characterized (Fig.9). The electrical tunability of the differential phase shift Δφ is achieved through the application of a voltage across BST. An insertion loss of 20 dB and a continuously variable differential phase shift as high as 650 degrees in the frequency range of 4.5-8 GHz are measured (Fig.10).

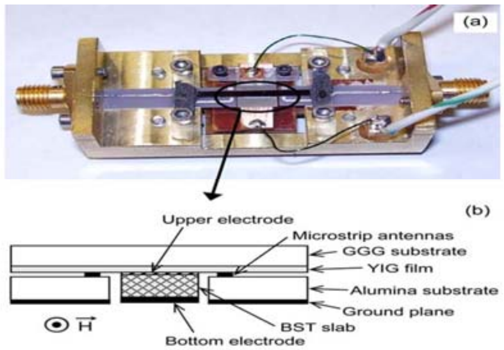

Fig.9: Experimental prototype of the YIG/BST phase shifter.

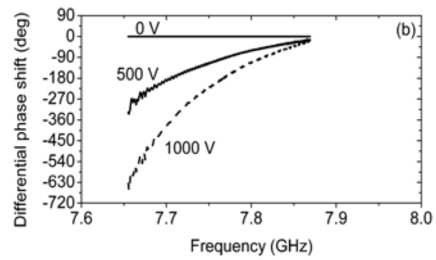

Fig.10: Frequency dependences of the differential phase shift measured for H=1939 Oe.

<u>Future plans</u>: We intend to extend this study to cover mm-wave magnetoelectric interactions and devices. A proposal has been submitted to ARO and is under review.

<u>References Cited</u>

<u>I. Publications: July 2004 – October 2007 (work supported by ARO grant)</u>

1. "Microwave magnetoelectric effects in single crystal bilayers of yttrium iron garnet and lead magnesium niobate-lead titanate," S. Shastry, G. Srinivasan, M. I. Bichurin, V. M. Petrov, and A. S. Tatarenko, Phys. Rev. B. **70**, 064416 (2004).
2. "Resonant Magnetoelectric Coupling in Trilayers of Ferromagnetic Alloys and Piezoelectric Lead Zirconate Titanate: The Influence of Bias Magnetic Field," G. Srinivasan, C. P. DeVreugd, V. M. Laletin, N. Paddubnaya, and M. I. Bichurin, Phys. Rev. B. **71**, 184423 (2005).
3. "Magnetoelectric Interactions in Bilayers of Yttrium Iron Garnet and Lead Magnesium Niobate-Lead Titanate : Evidence for Strong Coupling in Single Crystals and Epitaxial Films," G. Srinivasan, C. P. De Vreugd, M. I. Bichurin, and V. M. Petrov, Appl. Phys. Lett. **86**, 222506 (2005).
4. "Ferromagnetic-ferroelectric layered structures: Magnetoelectric interactions and devices," G. Srinivasan, M. I. Bichurin, and J. V. Mantese, Integ. Ferroelec. **71**, 45 (2005).
5. "Electrically tunable microwave filters based on ferromagnetic resonance in single crystal ferrite-ferroelectric bilayers," A. S. Tatarenko, M. I. Bichurin and G. Srinivasan, Elec. Lett. **41**, 596 (2005).
6. "Electrically tunable ferrite-ferroelectric microwave delay lines," Y. K. Fetisov and G. Srinivasan, Appl. Phys. Lett. **87**, 103502 (2005).

7. “Theory of magnetoelectric effects at magneto-acoustic resonance in single crystal ferromagnetic-ferroelectric heterostructures,” M. I. Bichurin, V. M. Petrov, O. V. Ryabkov, S. V. Verkin, and G. Srinivasan, Phys. Rev. B **72**, 060408 (R) 2005.
8. “A ferrite/piezoelectric microwave phase shifter: Studies on electric field tunability,” Y. K. Fetisov and G. Srinivasan, Elec. Lett. **41**, 1066 (2005).
9. “The floating zone crystal growth of ni, Co, Ni-Co, Ni-Zn, and Co-Zn ferrospinels under high oxygen pressure,” A. M. Balbashov, L. N. Rybina, Y. K. Fetisov, V. F. Meshcheryakov, and G. Srinivasan, J. Crys. Growth **175**, e733 (2005).
10. “Electric field induced shift of the magnetic resonance line in ferrite-piezoelectric composites, “ O. V. Antonenkov, M. I. Bichurin, D. A. Filippov, V. M. Petrov, and G. Srinivasan, Tech. Phys. Lett. **31**, 673 (2005).
11. “Ferrite-ferroelectric layered structures for electrically and magnetically tunable microwave resonators,” A. A. Semenov, S. F. Karmanenkov, V. E. Demidov, B. A. Kalinikos, G. Srinivasan, A. N. Slavin, and J. V. Mantese, Appl. Phys. Lett. **88**, 033503 (2006).
12. “Magnetoelectric coupling in bilayers of Pb(Zr,Ti)O3 epoxy and hot pressed manganite perovskite,” N. Zhang, X. Yin, M. Wang, T. Schneider, and G. Srinivasan, Chin. Appl. Phys. Lett. **23**, 463 (2006).
13. “Electric field tuning characteristics of a ferrite-piezoelectric microwave resonator,” Y. K. Fetisov and G. Srinivasan, Appl. Phys. Lett. **88**, 143503 (2006).
14. “A magnetoelectric microwave phase shifter,” A. S. Tatarenko, G. Srinivasan and M. I. Bichurin, Appl. Phys. Lett. **88**, 183507 (2006).
15. “A Magnetoelectric Microwave Band-Pass Filter,” A.S. Tatarenko, V. Gheevarughese, G. Srinivasan, Elec. Lett. **42**, 540 (2006).
16. “Dual-Tunable Hybrid Wave Ferrite-Ferroelectric Microwave Resonator,” A.A. Semenov, S.F. Karmanenko, B.A. Kalinikos, G. Srinivasan, A.N. Slavin, J.V. Mantese, Elec. Lett. **42**, 641 (2006)
17. “Ferrite-piezoelectric multilayers for magnetic field sensors,” Y. Fetisov, A. Bush, K. Kamentsev, A. Ostashchenko, and G. Srinivasan, IEEE Sensors **6**, 935 (2006).
18. “Microwave magnetoelectric effects and signal processing devices,” G. Srinivasan and Y. K. Fetisov, Integrated Ferroelectrics **83**, 89 (2006).
19. “Millimeter-wave magnetoelectric effects in bilayers of barium hexaferrite and lead zirconate titanate,” G. Srinivasan, I. V. Zavislyak, and A. S. Tatarenko, Appl. Phys. Lett. **89**, 152508 (2006).
20. “Electric field tunable ferrite-ferroelectric hybrid wave microwave resonators: Experiment and Theory,” A. B. Ustinov, V. S. Tiberkevich, G. Srinivasan, A. N. Slavin, A. A. Semenov, S. F. kamanenko, B. A. Kalinikos, J. V. Mantese, and R. Ramer, J. Appl. Phys. **100**, 093905 (2006).
21. “Magnetoacoustic resonance in tangentially magnetized ferrite-piezoelectric bilayers,” O.V. Ryabkov, V. M. Petrov, M. I. Bichurin, and G. Srinivasan, Tech. Phys. Lett. **32**, 1021 (2006).
22. “Microwave magnetoelectric interactions in multiferroics,” G. Srinivasan, A. S. Tatarenko, Y. K. Fetisov, V. Gheevarughese, and M. I. Bichurin, MRS proceedings, 2006.
23. “Ferrite-ferroelectric hybrid wave phase shifters,” A. Ustinov, G. Srinivasan, and B. A. Kalinikos, Appl. Phys. Lett. **90**, 031913 (2007).
24. “Structure, magnetism and tunable microwave properties of PLD-grown barium ferrite/barium strontium titanate bilayer films” R. Heindl, H. Srikanth, S. Watanachchi, P. Mukherjee, T. Weller, A. S. Tatarenko, and G. Srinivasan, in press, J. Magn. Magn. Mater. 2007.
25. “Magnetoelectric effects in porous ferromagnetic-piezoelectric bulk composites:Experiment and theory,” V. M. Petrov, G. Srinivasan, U. Laletsin, M. I. Bichurin, D. S. Tuskov, and N. puddubnaya, in press, Phys. Rev. B.

26. “Microwave Magnetoelectric Interactions in Ferrite-Piezoelectric Nanobilayers,” V. Petrov and G. Srinivasan, O. V. Ryabkov, S. V. Averkin, and M. I. Bichurin,” submitted to Appl. Phys. Lett. 2006.
27. “Effects of Exchange Interactions on Magneto-Acoustic Resonance in Layered Nanocomposites of Yttrium Iron Garnet and Lead Zirconate Titanate,” O.V. Ryabkov, S.V. Averkin M.I. Bichurin, V. M. Petrov and G.Srinivasan, submitted to JMR.
28. “Ferrite-piezoelectric layered structures: Microwave magnetoelectric effects and electric field tunable devices,” G. Srinivasan and Y. K. Fetisov, Ferroelectrics 342, 65 (2006).
29. C.Bayer, J.Jorzick, S.O.Demokritov, B.Hillebrands, R.Kouba, R.Bozinoski, A.N.Slavin, K.Guslienko, D.Berkov, N.Gorn, M.P.Kostylev, “Spin-wave excitations in finite rectangular elements of Ni80Fe20” , Phys.Rev.B 72 , 064427 (2005).
29. K.Yu. Guslienko, and A.N. Slavin, “Boundary conditions for magnetization in magnetic nanoelements”, Phys. Rev. B 72, 014463 (2005).
30. A. N. Slavin and V. S. Tiberkevich, “ Current-induced bistability and dynamic range of microwave generation in magnetic nano-structures”, Phys. Rev. B **72,** 094428 (2005).
31. A.N. Slavin and V.S. Tiberkevich, “Nonlinear self-phase-locking in an array of current-driven magnetic nano-contacts”, Phys. Rev. B **72**, 092407 (2005).
32. Slavin A.N**.**, Kabos P., “Approximate theory of microwave generation in a current-driven magnetic nanocontact magnetized in an arbitrary direction”, IEEE Trans. Magn. **41** , 1264-1273 (2005).
33.. S.O. Demokritov, V.E. Demidov, O. Dzyapko, G.A. Melkov, A.A. Serga, B. Hillebrands, and A.N. Slavin, “Bose-Einstein condensation of quasi-equilibrium magnons at room temperature under pumping”, Nature **443**, 430-433 (2006).
34. V.E.Demidov, U.-F. Hansen, O. Dzyapko, N. Koulev, S.O. Demokritov and A.N. Slavin, “Formation of longitudinal patterns and dimensionality crossover of nonlinear spin waves in ferromagnetic stripes”, Phys.Rev.B **74**, 092407 (2006).

II. Inventions/Patents

US Patent 7,201,817 - Granted April 10, 2007. "Multilayer composites for field conversion." - Srinivasan

US Patent 7,226,666 – Granted June 5, 2007. Magnetoelectric effects of magnetostrictive and piezoelectric composites.- Srinivasan

Patent Pending – Magnetoelectric microwave devices – 11/494,427 – Srinivasan